High-Cycle Fatigue Failure of Micron-Scale Polycrystalline Silicon Films for MEMS

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Previous research established that silicon MEMS can fatigue in ambient air environments but the mechanism of this failure mode has been a mystery for nearly a decade. We have recently identified the mechanism which appears to explain damage accumulation and failure of silicon thin films due to cyclic loading. We have termed this mechanism reaction-layer fatigue.

Stress-Life Behavior of Polycrystalline Silicon

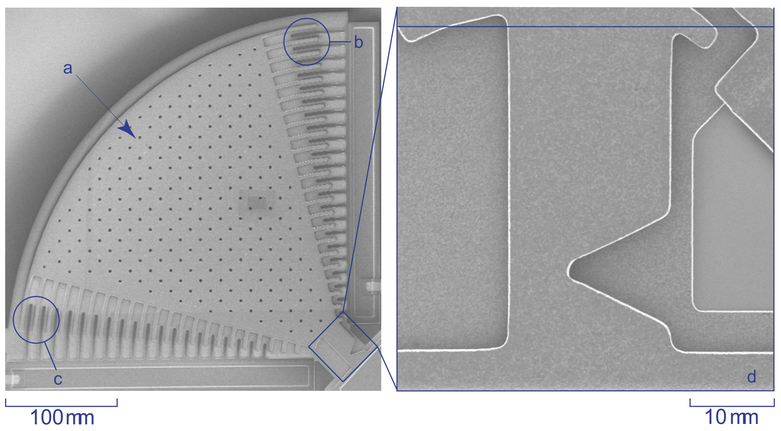

Figure 1: Scanning electron micrographs of the fatigue life characterization structure used in this investigation. The (a) mass, (b) comb drive actuator, (c) capacitive displacement sensor, and (d) notched cantilever beam specimen (inset) are shown. This 2 μm thick, surface micromachined structure was fabricated from LPCVD, n^+-type, polycrystalline silicon.

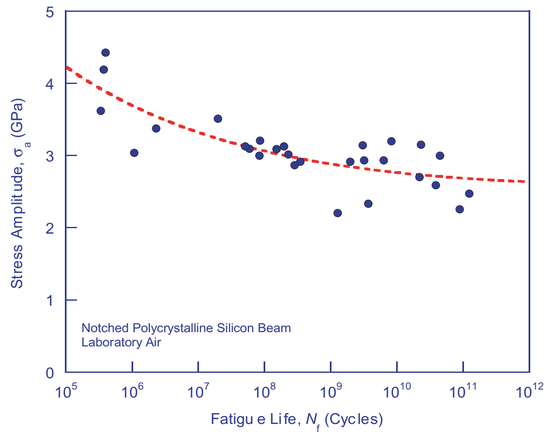

Figure 2: Stress-life (S/N) fatigue behavior of 2 micron thick, polycrystalline silicon at ~40 kHz under fully reversed, tension-compression loading. The dashed line is a fit of the stress-life power-law relation that is commonly applied to metals.

The Silicon Fatigue Mechanism - Reaction-Layer Fatigue

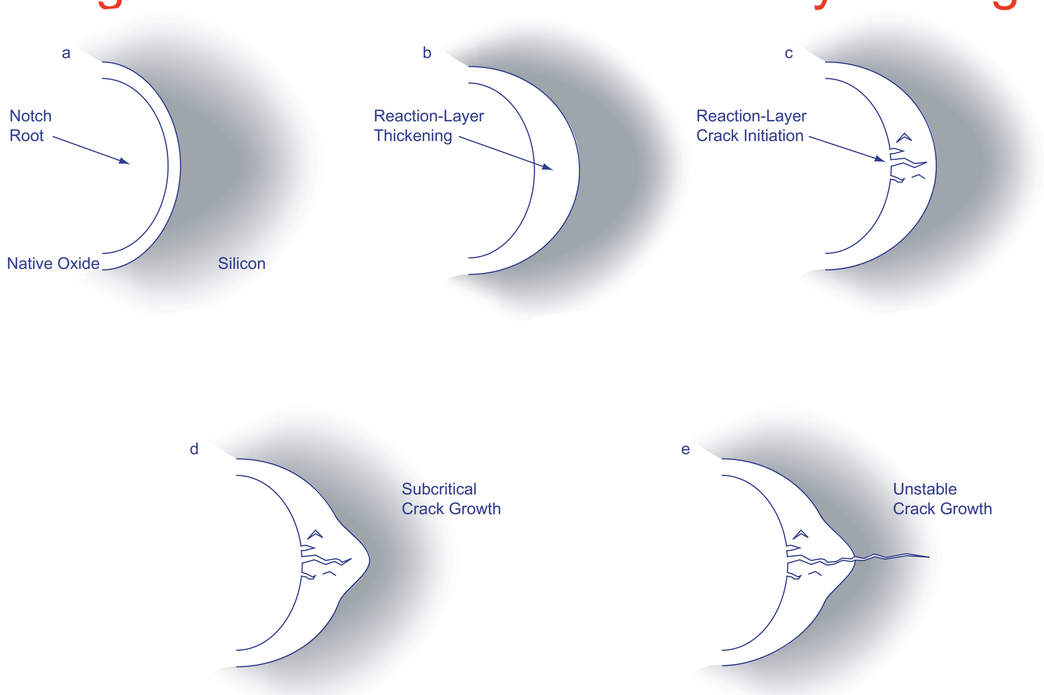

Figure 3: Schematic of the reaction-layer fatigue mechanism at the notch of the polycrystalline silicon cantilever beam. (a) Reaction layer (native oxide) on surface of the silicon. (b) Localized oxide thickening at the notch root. (c) Environmentally assisted crack initiation in the native oxide. (d) Additional thickening and cracking of reaction layer. (e) Unstable crack growth in the silicon film.

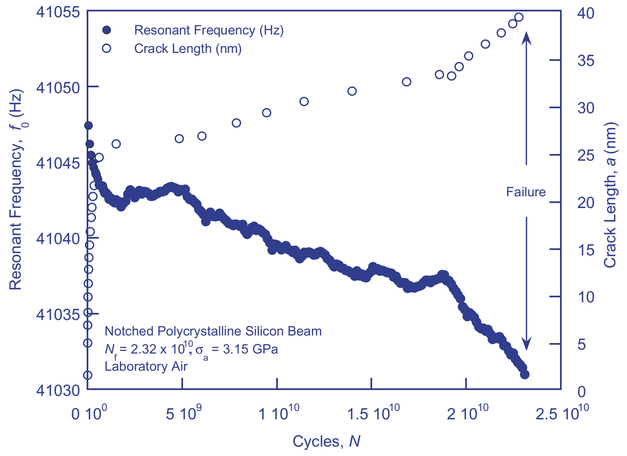

Figure 4: Damage accumulation in polycrystalline silicon, shown by experimentally measured decrease in resonant frequency, f_{crack}, with time during the fatigue test ($N_f = 2.23 \times 10^{10}$ cycles at σ_a = 3.15 GPa, and the corresponding computed increase in crack length, a.

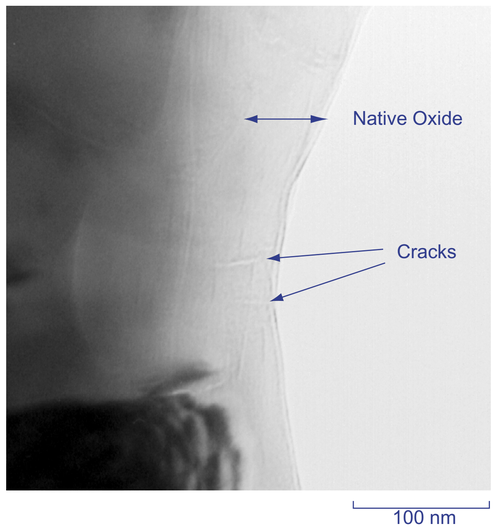

Figure 5 High voltage transmission electron micrograph showing stable cracks formed during cyclic loading in the native oxide of a notched, polycrystalline silicon beam. Testing interrupted after 3.56 x 10^9 cycles; stress amplitude of 2.51 GPa.

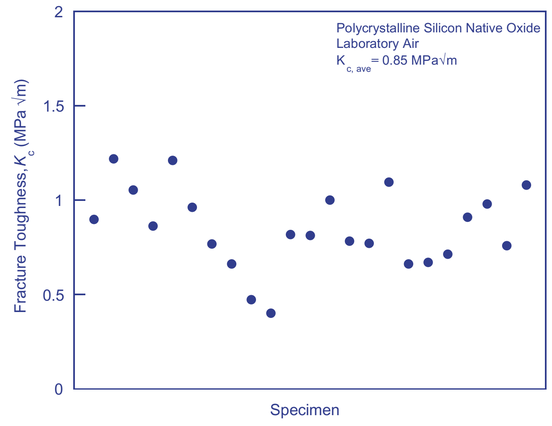

Figure 6: Computed fracture toughness, K_c, values determined from the estimated crack length immediately prior to failure, i.e., the critical crack size, a_c, for the given applied stress amplitude. The average fracture toughness of 0.85 MPa √m is consistent with failure within the native oxide on polycrystalline silicon at room temperature.

Recent Publications

Muhlstein, C.L., Stach, E.A. and Ritchie, R.O., "Mechanism of fatigue in micron scale films of polycrystalline silicon for microelectromechanical systems," *Applied Physics Letters*, 2002, vol. 80, pp. 1532-1534.

Muhlstein, C.L., Stach, E.A. and Ritchie, R.O., "A reaction-layer mechanism for the delayed failure of micron-scale polycrystalline silicon structural films subjected to high-cycle fatigue loading," *Acta Materialia*, 2002, vol. 50, pp. 3579-3595.

Muhlstein, C.L. and Ritchie, R.O., "High-cycle fatigue of micron-scale polycrystalline silicon films: fracture mechanics analysis of the role of the silicon/silica interface," *International Journal of Fracture,* 2002, in review.